Conference Paper

RADIATION HAZARDS IN SPACE

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ABSTRACT

A gross survey of data on energetic radiation in the environment of the earth will be presented. This will embrace the van Allen belt radiations, galactic cosmic radiations and solar cosmic radiations associated with solar flares. In the light of the current data the radiation problem will be analyzed in terms of shielding requirements to keep exposure down to "tolerable" limits in manned space flights. The estimates are preliminary especially in the cases of chance encounter with flare protons since calculations based on the available data give only upper and lower limits of physical doses. Also the contribution of secondaries to the biological effect is not finally known.

INTRODUCTION

We know today that mainly three kinds of energetic radiations exist in interplanetary space, which constitute a potential radiation hazard for manned space flight:

(1) The Van Allen belt radiations, energetic particles in substantial intensity trapped in the magnetic field of the earth and probably of planets.

(2) Galactic cosmic radiation, protons and heavier ions arriving from all directions of the galaxy, in part having extreme energies but

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*Aerospace Technologist.

of low intensity. This intensity in free space, of course, is substantially higher than that of their secondaries at sea level on earth, where man is protected by an atmospheric shield equivalent to 10 meters of water and by the magnetic field of the earth, which deflects these particles.

(3) Solar cosmic radiation, identified during the geophysical year as transient energetic proton showers (in some cases of high intensity and duration) associated with flare erruptions on the sun. Flares are intense chromospheric light flashes in the visible and ultraviolet part of the spectrum accompanying these violent erruptions.

Although our knowledge about the characteristics of space radiations, that is about composition, energies, spatial distribution, intensities, and their variation with time, has substantially increased in the last 10 years; nevertheless these data are fragmentary especially on belt and solar cosmic radiation. Furthermore, the biological significance of the energetic space radiations and especially of their secondaries dependent on the structure of the space vehicle is not fully explored. For these reasons, only first approaches are made to indicate the levels of anticipated dose rates and doses behind various amounts of shielding, for describing in a quantitative manner the radiation hazard in space.

It is the intent of this survey to summarize without detail estimates particularly those made under contract of NASA or ABMA or by NASA itself in the light of current data.

Belt radiation in galactic and solar cosmic rays are neither of equal intensity nor uniformly distributed in space, nor are they, as in the case of solar proton streams, always present. The accumulated dose depends, therefore, except for wall thickness of the vehicle or shielding, on the trajectory and on the date and the duration of the mission that we have in mind. Not to go into details, we assess only upper limits of exposure that may occur under unfavorable conditions, ignoring means to avoid these radiations in their full intensity, e.g., by choosing appropriate trajectories.

In the beginning it may be useful to recall the definitions of some radio biological units and terms that are used in the following. (See appendix.)

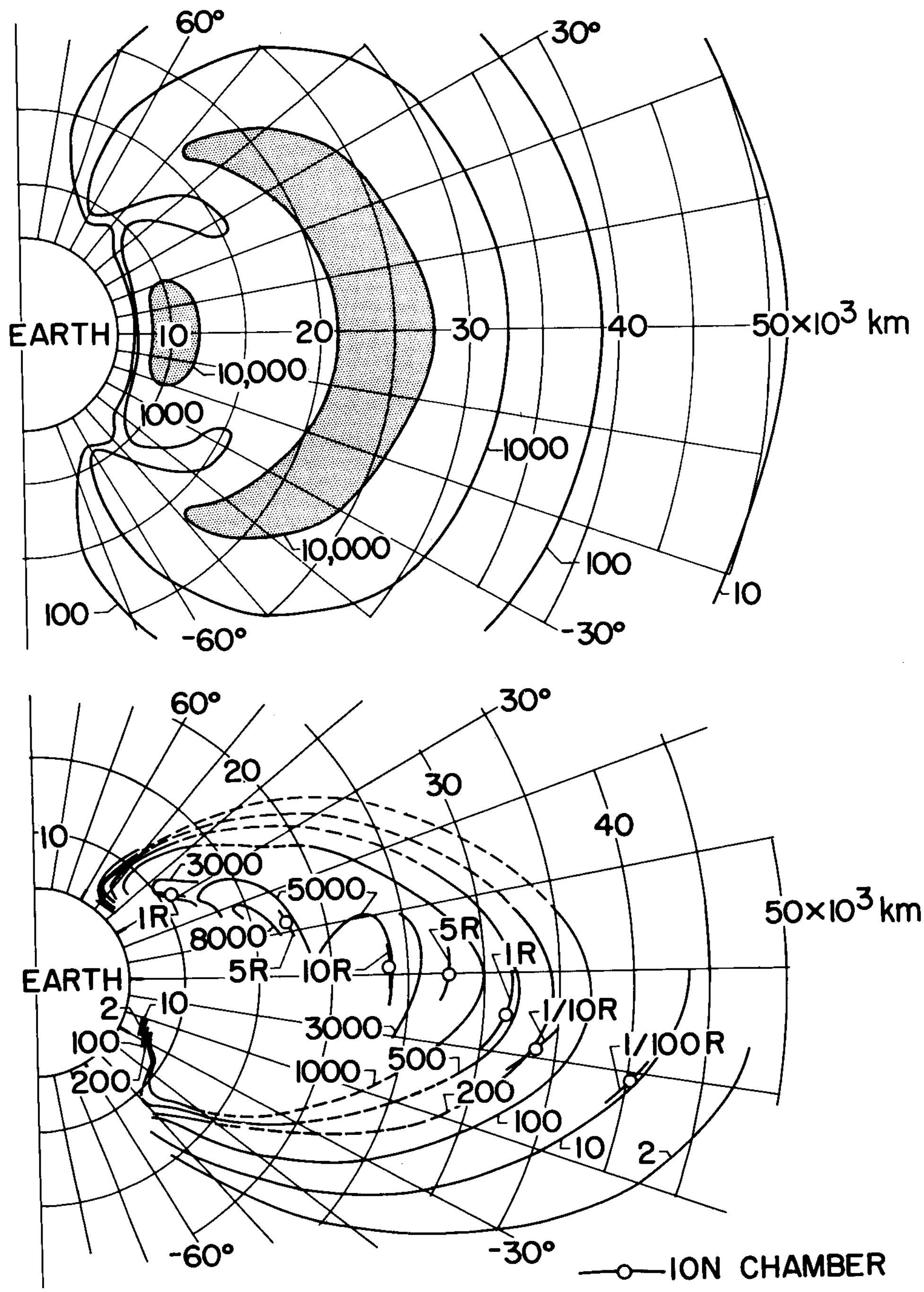

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Figure 1.- Comparison of the counting rate contours in the radiation zone as given by Van Allen (upper) and as given by analysis of Explorer VI (lower) shown on a polar plot. It is apparent that the radiation zones during the time of Explorer VI have shrunken considerably and changed form since those inferred from the Explorer IV and Pioneer III and IV data.

I. VAN ALLEN BELT RADIATIONS

(1) Spatial distribution

Figure 1 presents a survey of the spatial distribution and the intensities of the energetic belt particles. In the upper part of figure 1 the isocount lines are drawn by Van Allen according to counter measurements (refs. 1, 2, and 3) with satellites Explorer I, Explorer IV, and in the outer region with Pioneer IV, March 3, 1959, after a major solar activity period. The results indicate two regions of maximum intensity, one at 10,000 km from the earth's center and a more distant region at about 25,000 km distance.

In the lower part of figure 1 are shown isocount contours and measurements of Winckler and coworkers (ref. 4) with ionization chamber in Explorer VI at quiet times (August 1-16, 1959). At this time the outer region is considerably shrunken and shows two maxima of intensity. During magnetic storms following this quiet period, further depletion of the outermost zone was observed. This depletion was, in turn, followed by a large increase in the intensity and expansion of the outer belt. The intermediate belt disappeared and similar count contours were obtained such as those in the upper part of figure 1. Detailed investigations including rockets reaffirmed that the inner belt can be identified with energetic proton and electron fluxes which are relatively stable during solar activity. Substantial proton fluxes in the energy range 10 to 400 Mev are measured. In the outer zones, only electrons with energies up to 2 Mev in the average 40 kev and no energetic protons are observed.

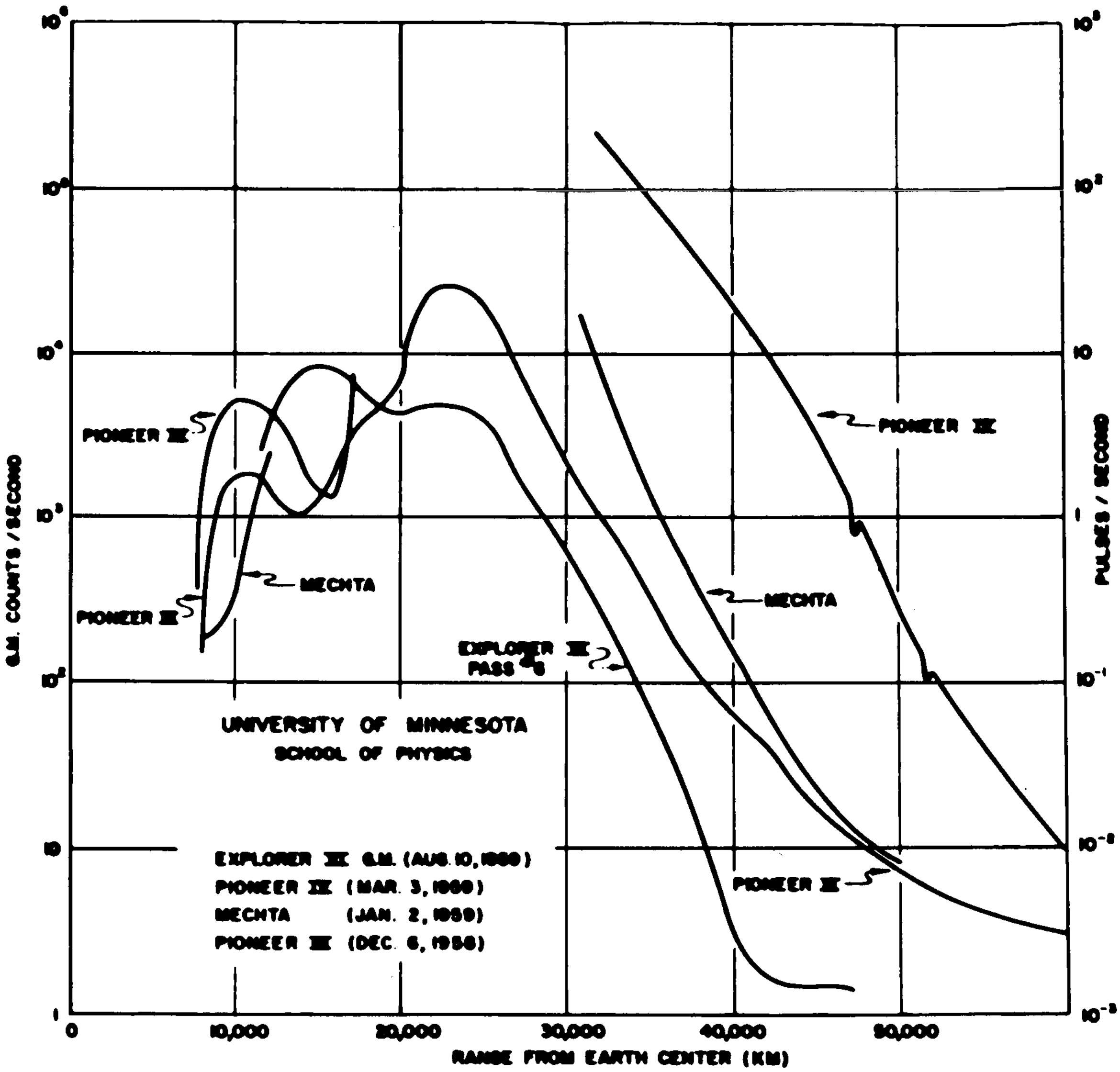

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Figure 2.- Comparison of Geiger counter rates for Explorer VI, Pioneer III, Pioneer IV, and the Russian Mechta space probe. The various counting rates are on a comparable basis within approximately 25 percent. Explorer VI shows the lowest intensity of trapped radiation and Pioneer IV the greatest enhancement of the radiation regions. These curves illustrate the time variability of the outer regions over long periods.

A more quantitative comparison of the variation of intensities in the outer zone can be obtained from figure 2 (ref. 4), which shows the counts in lightly shielded counters during flights radial outwards. Pioneers III and IV had almost identical counters (shieldings $1 g/cm^2$ of the same material) and nearly identical trajectories. We recognize that the counts at about the same location vary by a factor 100 or more at different times.

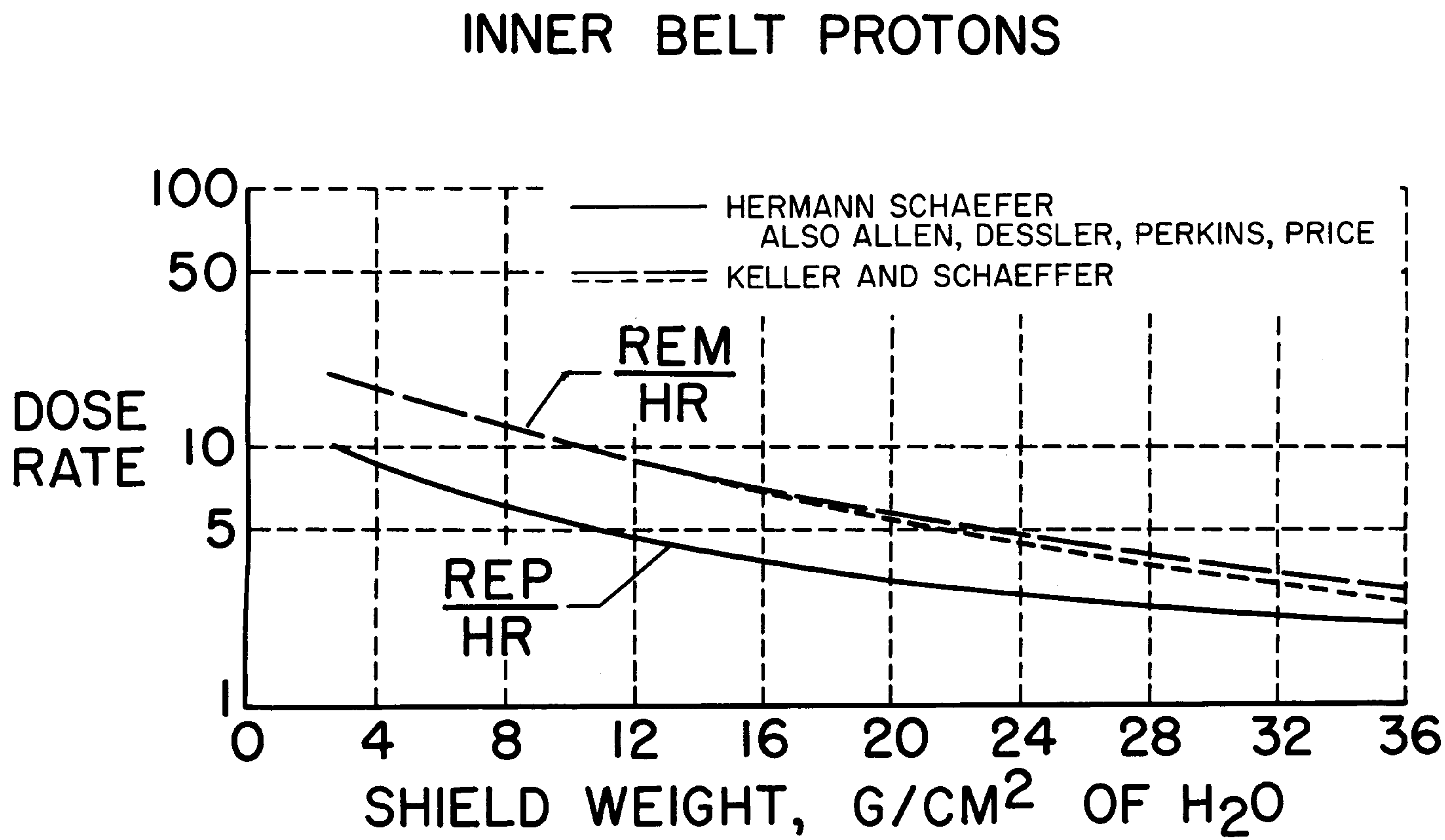

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Figure 3.- Dose rates in center of spherical shield neglecting self-shielding of the body.

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(2) Proton dose rates (inner belt)

To calculate the dose rates behind various amounts of shielding arising, for example, from inner belt protons we have to know the maximum flux values and the energy spectrum of the particles.

Considering the maximum overall flux of energetic protons in the center of the inner belt (at longitude ~70° west and altitude ~3,000 km above the earth near the magnetic equator), Van Allen found

$$N = 20{,}000 \ \frac{\text{Protons}}{\text{cm}^2 \ \text{sec}}$$

having energies >40 Mev. This value is considered as trustworthy by a factor 2; that is, the flux may be up to 40,000 protons/cm^2 sec in the center.

The spectrum of protons above 75 Mev in the inner belt was first measured with nuclear emulsions by Freden and White (ref. 5), but only near the lower belt boundary at 1,200 km altitude near Cape Canaveral, 80° west. The flux was extrapolated down to 40 Mev as 1,000 protons/cm^2 sec (at 1,200 km altitude near the Cape in low magnetic latitudes, 20° to 30° N). Based on this spectrum, detailed calculations of the dose rate were first made by Hermann Schaefer (ref. 6) at the Naval School of Aviation Medicine, and later by Keller and Schaefer (ref. 7), at that time with Convair under contract with NASA, as well as by Allen, Dessler, Perkins, and Price at Lockheed under contract with ABMA (ref. 8).

Assuming the above spectrum and 20,000 protons/cm^2 sec > 40 Mev in the center, the results are essentially the same and are shown in figure 3.

H. Schaefer* and Allen, Dessler, and coauthors come to essentially the same dose rate in rep/hr behind different amounts of shielding (lowest curve). The higher values of W. Keller and coauthor in rem/hr are partly caused by the assumption that protons of energies < 40 Mev have an RBE = 2 and partly by a somewhat different extrapolation of the low energy part of the spectrum. Under the assumption that the spectrum has the same shape in the center of the inner belt as at the inner edge and neglecting self-shielding and assuming a maximum value of 20,000 proton/cm^2 sec > 40 Mev, thus inside a spherical water shield the following dose rates are obtained:

Wall thickness	2g/cm^2 of H_2O	25g/cm^2 of H_2O
Dose rate	12 rep/hr	2.7 rep/hr

For 40,000 protons/cm^2 sec in the belt center, the dose rates for the same shielding are 24 rep/hr and 5.4 rep/hr, respectively. We note that the dose rate decreases only by a factor 1/4 to 1/5 by using a heavier shield of 25 g/cm^2 of H_2O or carbon.

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*The lower curve in figure 3 is deduced from H. Schaefer's "Bragg" curve for a parallel beam with Freden-White's energy spectrum by multiplying by the factor $20 = \frac{20{,}000 \text{ p/cm}^2 \text{ sec, center}}{1{,}000 \text{ p/cm}^2 \text{ sec, 1,200 km}}$ not considering self-shielding of the body. Schaefer calculated also the self-shielding effect and dose rate distribution inside of a body phantom (75 kg water sphere) behind different amounts of outer shielding based on this Bragg curve.

It may be mentioned that the increase of the particle number on the low energy end of the spectrum (<20 Mev energy) according to measurements of Naugle (ref. 30) should not change the numbers for high shielding thicknesses substantially, because the range of protons of 20 Mev is about 0.5 g/cm^2 for material of low Z number. Of course, an amount of secondaries, especially neutrons, will appear additively from nuclear collisions and subsequent evaporations that are not taken into account here. In order to provide for possible error in the intensity of low energy primary protons and their secondaries and also for variations in the intensity that have been recently reported, the number of 24 rep/hr appears preferable as the maximum proton dose rate in the center of the inner belt.

Estimates taking into account secondaries from nuclear collisions, especially fast neutrons, are carried out in references 7 and 8 for different structure and shielding materials like Be, C, Mg, and Al, with the result that the contribution to the physical dose rate for shielding thicknesses of the order of 20 g/cm^2 is about 10 percent in first approximation. It seems advisable to refine these calculations also taking into account the contribution of neutrons produced by low energy protons (<20 Mev) and boil off neutrons, which may be high (e.g., for Be) and to estimate the biological dose rate in supplementing considerations. More detailed computations are carried out by W. Keller (ref. 7a) for carbon as shielding material and show that such secondary radiation is important and must be considered in detailed shield designs.

(3) X-radiation inside the vehicle

With regard to shielding requirements for the crew, X-radiation inside the spacecraft, produced by electrons of the inner and outer belt impinging on the surface of the spacecraft must be considered (electrons, e.g., of 100 kev have only a range of 1/10 mm in aluminum and do not penetrate the shell directly).

In the outer belt the flux values of electrons fluctuate in wide limits as was shown before (fig. 1).

In quiet periods Winckler (ref. 4) measured directly 10 r/hr with an ionization chamber of 1/2 mm aluminum wall thickness. In the expansion phase after magnetic storms, the dose rate increased to 30 r/hr in Explorer VI.

Van Allen calculated 100 r/hr inside 1 g/cm^2 Al in the zone of maximum intensity, during the time of the Pioneer IV flight, when the outer belt was most expanded and intense. We limit the discussion here to a rough estimate of dose rates inside the vehicle, since they are strongly dependent on constructive details such as wall materials, thicknesses, and coating. Although the electron fluxes and the aforementioned dose rates are high - the electron flux $E > 20$ kev is estimated by Van Allen as 10^{11} e/cm^2 sec as the peak of the outer belt during the flight of Pioneer IV - the shielding problem is of lower magnitude than that of shielding against protons in the inner belt. The electron spectrum and the produced X-radiation decrease steeply with energy in their intensity and the latter can be easily reduced by 1 to 2 mm of uranium or lead by at least a factor 1/20 to <5 r/hr. The same effect would be produced by about 10 g/cm^2 of aluminum. The production of X-radiation can be further reduced by a thin coat of carbon on the outside - by a factor 1/3 against, for example, aluminum - since the produced bremstrahlung intensity is proportional to the Z number.* We obtain thus as an upper limit a dose rate on the order of 1 to 2 r/hr in the spacecraft, neglecting self-shielding of men's bodies, in a space ship with shielding equivalent to 10 g/cm^2 of aluminum and carbon coating in the maximum of the outer belt. More detailed calculations were again carried out by the Lockheed group (ref. 8), as well as by W. Keller (ref. 7), Dye and Noyes (ref. 9), Prof. Robley Evans of M.I.T. (ref. 24), using the spectra given by Van Allen (ref. 2), Holly and Johnson (ref. 11), Walt, Chase, et al. (ref. 10). The calculations of the Lockheed authors and R. Evans lead to substantially lower dose rates than given above.

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*Z-number, charge of the nucleus.

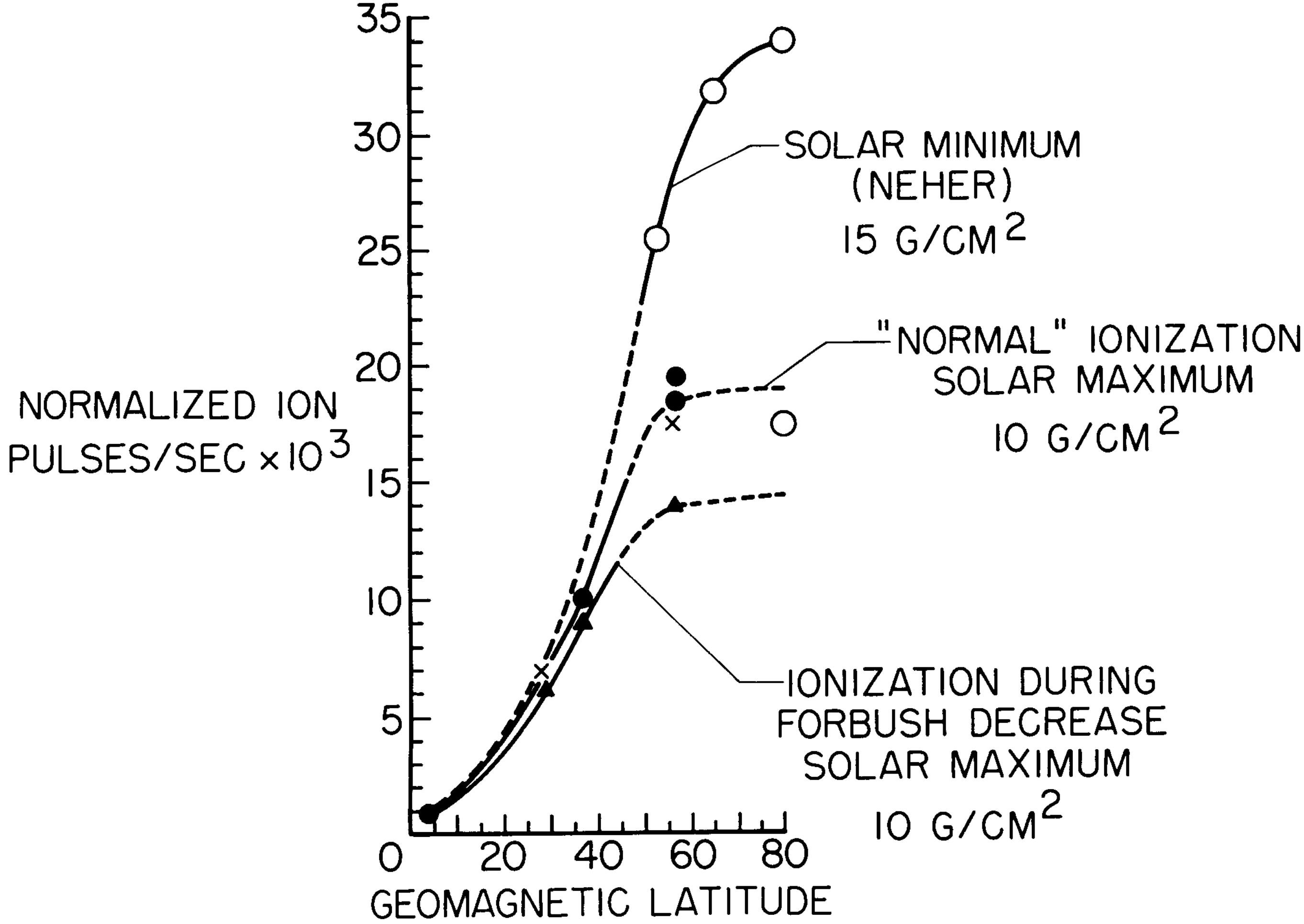

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Figure 4.- Total ionization in 10 g/cm^2 depth as a function of geomagnetic latitude at solar minimum and maximum. (Reproduced from ref. 9, J. R. Winckler.)

II. GALACTIC COSMIC RADIATION

(1) Intensities and overall ionization dosage

The primary galactic cosmic radiation consists of positively charged atomic nuclei of high energy, mostly protons (~85 percent), α particles (~12 percent), and a few heavier nuclei observed up to tin (Sb), stripped of all electrons. Figure 4 gives an illustration of the cosmic ray intensities near the earth and their variation with solar activity. It shows a meridional cross section of the overall ionization on top of the atmosphere (for about 10 g/cm^2 atmospheric depth, i.e., 100,000 ft or 30 km altitude) produced by galactic cosmic rays impinging from all directions of the sky. As is shown near the origin of the abscissa, the ionization above the magnetic equator at 30 km altitude is low and is about equal during solar maximum and solar minimum years as a result of the shielding effect of the magnetic field of the earth. On the poles, where the lower energy particles are less deflected, at 30 km altitude the ionization is higher by a factor of 35 during solar minimum years and by a factor of 20 during activity years. This increase of ionization during solar minimum years by a factor of about two on the poles and not on the equator reflects the fact that the low energy part of the primary spectrum is increased during this period. This can be caused by the low energy primaries only, since these have access to the poles but not to the magnetic equator. The biological significance of this information is discussed subsequently (Part II(2)).

During solar activity years sudden further decreases of ionization of as much as 25 to 30 percent are observed. These so-called "Forbush decreases" are associated with solar flare activity. Simultaneous observations (13) of such decreases both on earth and aboard Pioneer V (1960 Alpha) during 1960 and at 5,000,000 kilometers from the earth indicate that they are due not to distortion of the earth's magnetic field but to interplanetary magnetic clouds associated with ejected solar plasmas.

From the general viewpoint of implications to space flights, the most important fact is that the flux of galactic cosmic rays in interplanetary space is very low in comparison with the flux in the belt or in major solar proton beams, namely

$$N = 2.5 \frac{\text{Particles}}{\text{cm}^2 \text{ sec}}$$

during solar activity years. It may be supposed, therefore, that the normal ionization dosage of galactic cosmic rays lies under any acute level. Carefully taking into account the higher specific ionization of heavier primaries and their higher RBE, a dose rate of about 0.45 rem/week is calculated in free space, if no shielding is provided, except self-shielding of the body (ref. 14), and secondaries produced in the body are disregarded. This dose rate is on the order of the maximum permissible dose rate for atomic and medical workers (up to 1958, 0.3 rem/week). According to more conservative recommendations of the ICRP, 1959, the maximum permissible dose rate is 0.1 rem/week or

5 rem/year for persons from ages 18-68 or a total of 250 rem during an adults lifetime. Thus the normal ionization dosage by galactic rays should at least not lead to acute or disabling symptoms, even if the spacecraft crew is exposed to this space radiation for a year or more (25 to 50 rem), and even if secondaries produced inside the body and in the vehicle material double this dose (50 to 100 rem/year). Shielding, to reduce this overall ionization dosage produced by galactic cosmic rays, say for the solar minimum years where the ionization is higher by a factor of about two, would be a very expensive task, especially in terms of weight. (See also ref. 14.) The reason is, that shields up to 80 g/cm^2 even of low Z number material, reduce the dose rate only by a small amount or even increase the dose rate during solar activity years, when apparently the low energy part of the primary spectrum is cut off by interplanetary magnetic fields. With such high energy beams a buildup of secondaries occurs as has been observed in the atmosphere for a depth of about 60 to 80 g/cm^2 during solar activity years. During minimum solar activity years this transition effect is covered by the ionization produced by low energy primaries.

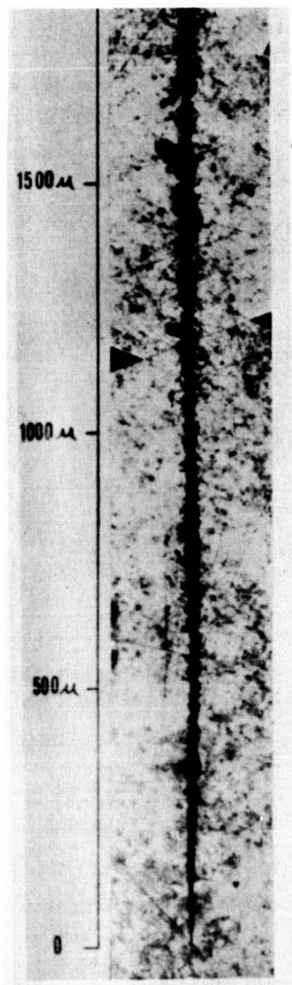

Figure 5.- Ionization peak and thin-down part of a heavy nucleus track of $Z = \sim 50$ (tin) recorded at 105,000 feet and 55° N latitude with emulsion chamber method, by Herman Yagoda, Laboratory of Physical Biology, National Institutes of Health.

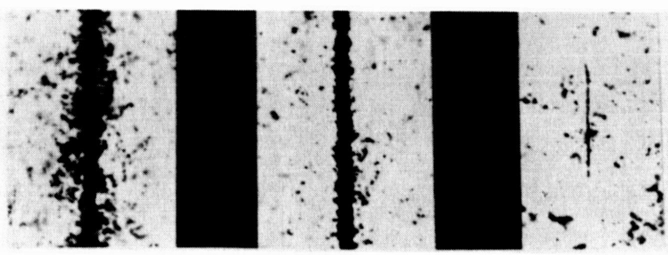

Figure 5(a).- Microphotograph of two sections of a heavy nucleus track $Z = 20$, and a thorium alpha track (E. P. Ney and Ph. Freier, University of Minnesota). Left. Heavy nucleus of 4,000 million eV energy. Center. Heavy nucleus at 400 million eV energy. Right. Thorium alpha track. Total vertical length of the visual field, 58 micra.

(2) Heavy primary hits

As emphasized by Hermann Schaefer, Yagoda, Tobias, Haymaker, and other scientists, the biologically most efficient component of the galactic cosmic ray beam should be not the overall ionization dosage produced in the body but the number of slow heavy primaries, which come to rest by electronic collisions in the unshielded body.

Figure 5 (ref. 16) shows the ionization spread and thin-down part of such heavy primaries that come to rest by normal ionization without undergoing nuclear collisions, in comparison with the ionization track of a Thorium α particle (right side of fig. 5(a)). The density of the ionization column around the track increases with Z^2 where Z is the atomic number or charge of the impinging particle. In the core of the column occur doses of 10^4 to 2×10^4 roentgen. The biological effect of such broad columns of ionization with a diameter comparable with the diameter of living cells (10μ) is considered as much more profound than corresponds to their contribution to the overall ionization per volume or gram (the latter is low, ≈ 5 percent at the top of the atmosphere). The number of thin down hits per unit volume of the body is therefore a more adequate measure of their biological effect than their contribution to the dose in rep or rad.

To give an order of magnitude of the number of hits on top of the atmosphere the results obtained during the Man High II balloon flight, August 1957, may be recalled (ref. 17). During a stay of 15 hours in over 90,000 feet altitude (in latitude $>55^{\circ}$), the number of calcium ($Z = 20$)

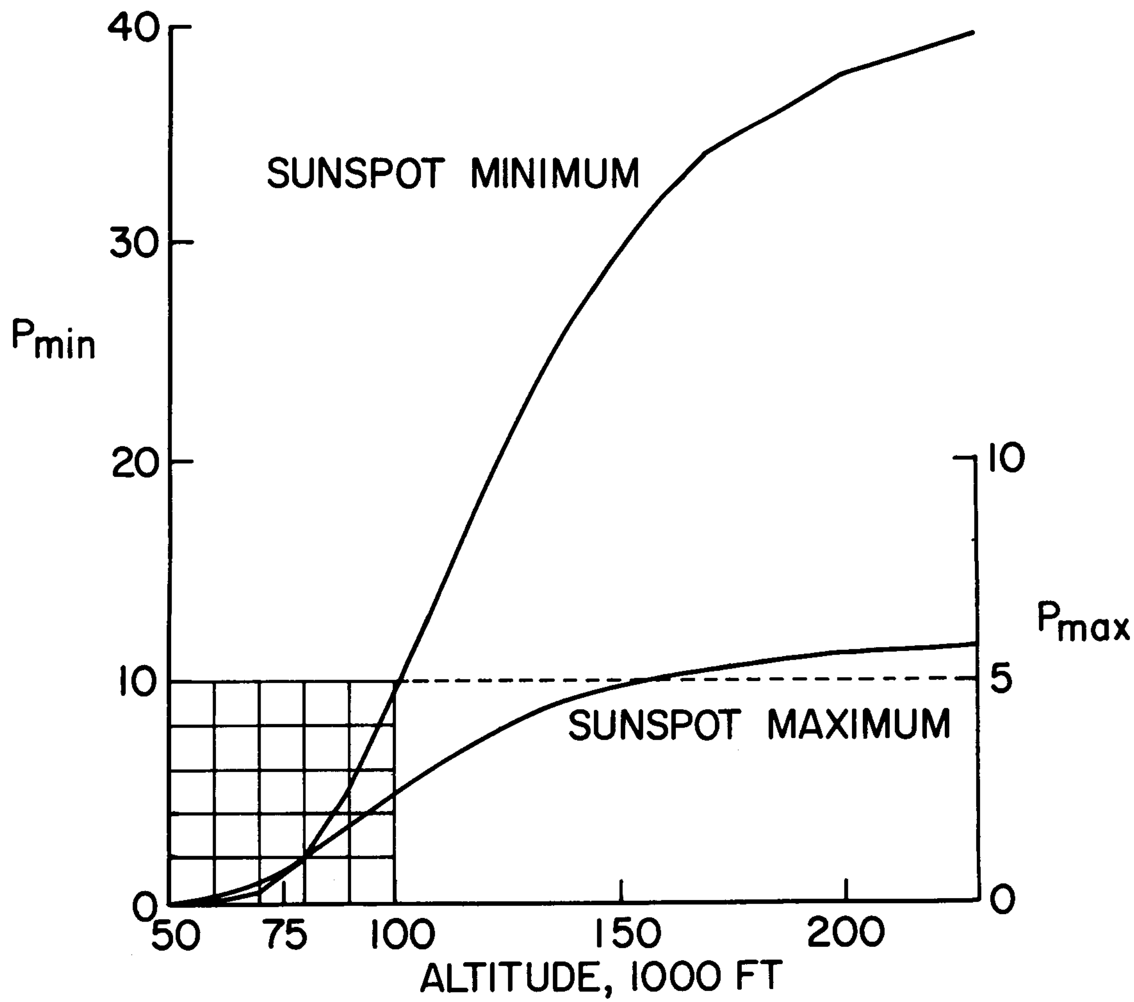

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Figure 6.- Variation of thindown intensities with altitude for seasons of maximum and minimum sunspot activity. (Reproduced from ref. 18, H. Jagoda.)

up to iron (Z = 26) hits recorded in three emulsion pellicles 3 × 4 inches 600μ thick placed on the arms and the chest of the pilot were 3, 1, 2.

The number of lower Z number hits was in the order of 25 per pellicle. The number of hits $Z > 6$ in the whole body during this 15-hour flight is estimated to have been about 150,000 (volume of the body ~ 75,000 cm^3). Although this total number appears high, the number per cubic centimeter is only ~2. It was not possible to detect significant biological effects after the flight during subsequent weeks and years of observation. The number of hits/cm^3 that can produce significant effects on man is as yet not clear. At this time one cannot exclude that the heavy primaries may constitute a radiation danger for expeditions of long duration in a lightly shielded space vehicle. Fortunately, the shielding against low energy heavy primaries is a much easier task than shielding against the high energy protons and secondaries with low charge. The heavy primaries come to rest by normal ionization in relatively low shield thicknesses because of their high energy losses or, if more energetic, degrade in nuclear collisions in particles of the lightly ionizing type and those of presumably lower biological effectiveness, because of their larger cross sections. Especially favorable in terms of weight for protection against thin down hits is low Z number material, as it is also for protection against protons and their secondaries. Preliminary estimates indicate that a spherical shield having a thickness equivalent to 20 g/cm^2 of H_2O would be necessary to reduce substantially the number of hits in a target like man's body. The shielding effect of the atmosphere against heavy primaries can be observed in the curves of figure 6 extrapolated from

Yagoda (ref. 18) from careful emulsion measurements in high altitude balloons in high latitudes. P is the number of hits/cm^3 per day. The number of hits in 20 g/cm^2 depth of atmosphere (87,000 feet, 26.4 km altitude) is reduced by a factor of 1/10 during solar minimum years and by a factor of 1/5 during activity years.

III. SOLAR COSMIC RAYS

As the third and most important problem, the radiation hazard of energetic solar flare particles has to be considered. This solar cosmic radiation was detected at sea level in some events as early as 1942 by Forbush and Ehmert. Such high energy events that penetrate with their secondaries to sea level are rare. Since the direct measurement of solar protons of lower particle energy in balloons by Winckler in 1957, which are more frequent and are observable only in high altitudes and latitudes, distinction is made between high energy events with relativistic particle energies up to 20 Bev but having generally lower intensities, and low and medium energy events with particle energies up to 400 Mev or few Bev, respectively, in some cases of extreme intensity.

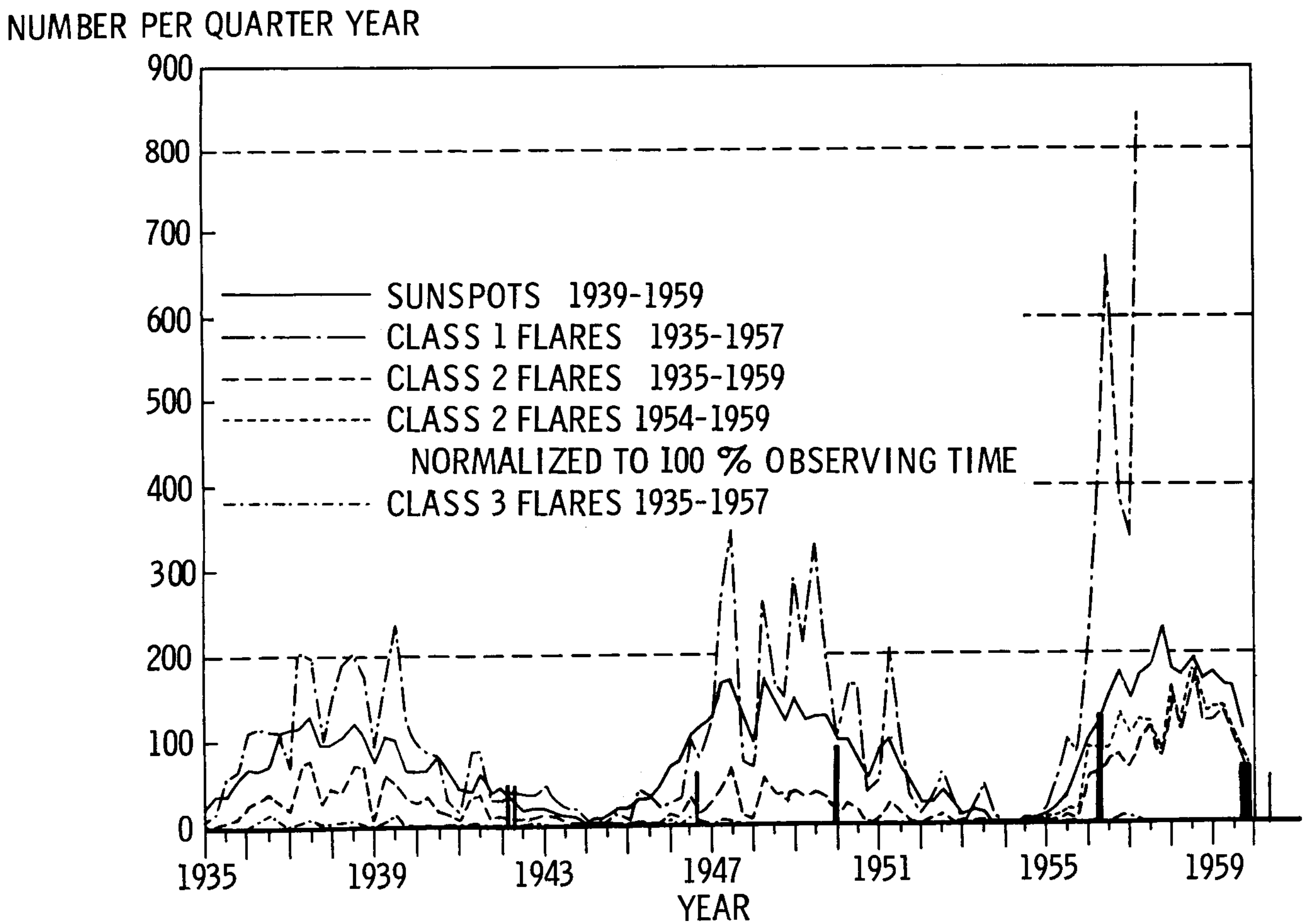

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Figure 7.- Frequencies of sunspots and flares in the last solar periods and high energy proton events. (Courtesy J. W. Evans, Sacramento Peak Observatory, New Mexico, AFCRC.)

(1) Frequencies

The frequency of high energy events in the three last solar cycles including one medium energy event is given in figure 7. One or two high energy events are observed every 4 to 5 years along the rising and falling slope of a sunspot cycle. The most energetic and intensive event since 1938 occurred on February 23, 1956. The frequency of low and medium energy events are shown in figure 8 (modified from ref. 19, see also ref. 20). About 5 to 13 events occurred per year, that were intense enough to be detectable with riometers* or in instrumented high-altitude balloons, in high latitudes. Most of these low energy events do not constitute a danger in a space vehicle shielded by about 5 to 10 g/cm^2 of low Z number material because of their low intensity.

Extreme flux low and medium energy events, which produce a radio attenuation of 15 db and more (28 Mc) constitute, however an appreciable hazard (indicated by circles in fig. 8). Of such extreme events only 2 to 4 per year occurred during the last years of high solar activity. Of course, sometimes 2 or more occurred in very short succession within a few days, like the events on July 10, 14, 16, 1959 and the events on November 12 and 15, 1960.

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*Radio ionospheric opacity meter, measures the cosmic radio noise absorption at 28 and 50 Mc in the lower ionosphere (30 to 80 km) caused by penetrating ionizing particles.

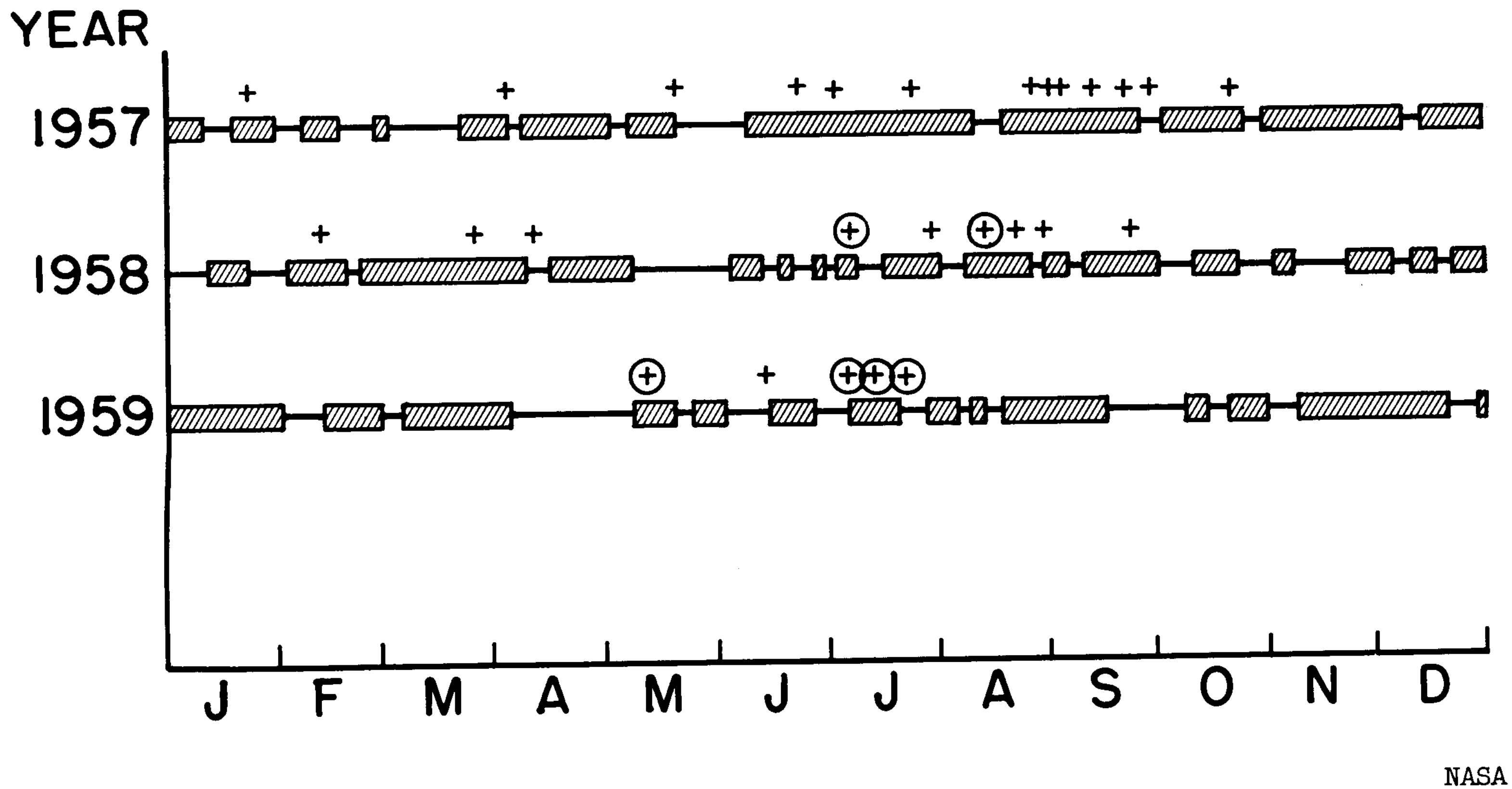

Figure 8.- Frequency of low and medium energy solar events and correlation with large penumbral areas of sunspots.

(2) Prediction of quiet periods. Encounter probabilities.

A second purpose of figure 8 is to indicate a correlation provided by Kinsey Anderson (ref. 19) between occurrence of penumbral areas around sunspot groups that exceeded a critical area and proton events. These times of large penumbras are indicated by hatched boxes. In all except two instances no solar events occurred during periods of absence of penumbral areas; and when such events occurred, they were not earlier than 2 days after the increase of penumbral areas. On the basis of Anderson's analysis of the years 1952 to 1959 it appears that absence of major events can be predicted for excursion times of 2 to 4 days with acceptable reliability. For an excursion of 7 days however, in three cases of 55 a strong event would have been encountered against prediction. On a purely random statistical basis of occurrences, the probability of encountering an extreme event in a 10-day trip would be $\frac{4}{36.5} = 0.11$ or 11 encounters in 100 flights, assuming according to the experience of recent years, four extreme events per solar activity year. The probability of encountering two events or more would be 0.006 or 0.6 percent. It is to be noted, however, that these events, tend to occur in bunches. By investigation of the last three solar cycles, on the basis of a correlation between flare events and large magnetic disturbances as measured by a magnetic index $A_p > 80$, Adamson and Davidson (ref. 21) found that the bunching effect diminishes the probability for one event by a factor 0.8 and increases the probability for two or more events in a 10-day excursion by a factor >2, to about 1.2 percent. These encounter probabilities for short time excursions are considered as too high to be ignored, and as long as no reliable prediction criteria are found, an amount of shielding is recommended that reduces the dose accumulated in two or three events to tolerable limits even for expeditions of only 10 to 14 days duration in space. Adequate shielding appears indispensible for excursions of longer duration during solar activity years, such as a Mars expedition, which would take more than a year.

3. Maximum fluxes and spectra

To obtain a survey about dose rates and doses which can occur in a space vehicle during such events, we have again to know the fluxes and the spectra, and equally important, their timely variations especially during the maximum intensity phases.

Referring to maximum intensities, we know that the fluxes of energetic protons of various events vary in wide limits - by about six orders of magnitude - from cosmic ray background intensity of 2.5 p/cm^2 sec, corresponding to a dose rate of 0.1 rep/week up to possibly 10^6 protons/cm^2 sec corresponding to thousands of rep/hour behind a small amount of shielding. To obtain upper limits of doses we consider only fluxes and spectra of the most extreme events observed in the last solar cycle, as given in figure 9.

The fluxes of particles having energies $> E$ are plotted against the energy E in Bev on the abscissa. These spectra have a common characteristic, they fall off much more steeply in the higher energy range than the spectra of the inner belt protons or of galactic cosmic protons. This leads to the expectation that by practical shielding amounts in the order of 30 g/cm^2, the main intensity can be cut off, at least for low and medium energy events; for example, in the May 1959 low energy event after 33 hours using a 30 g/cm^2 H_2O shield corresponding to the range of 220 Mev protons, only ~100 protons/cm^2-sec sterad with $E > 220$ Mev penetrate the shield; the 10^4 times higher flux of particles $E < 220$ Mev is absorbed in the shield.

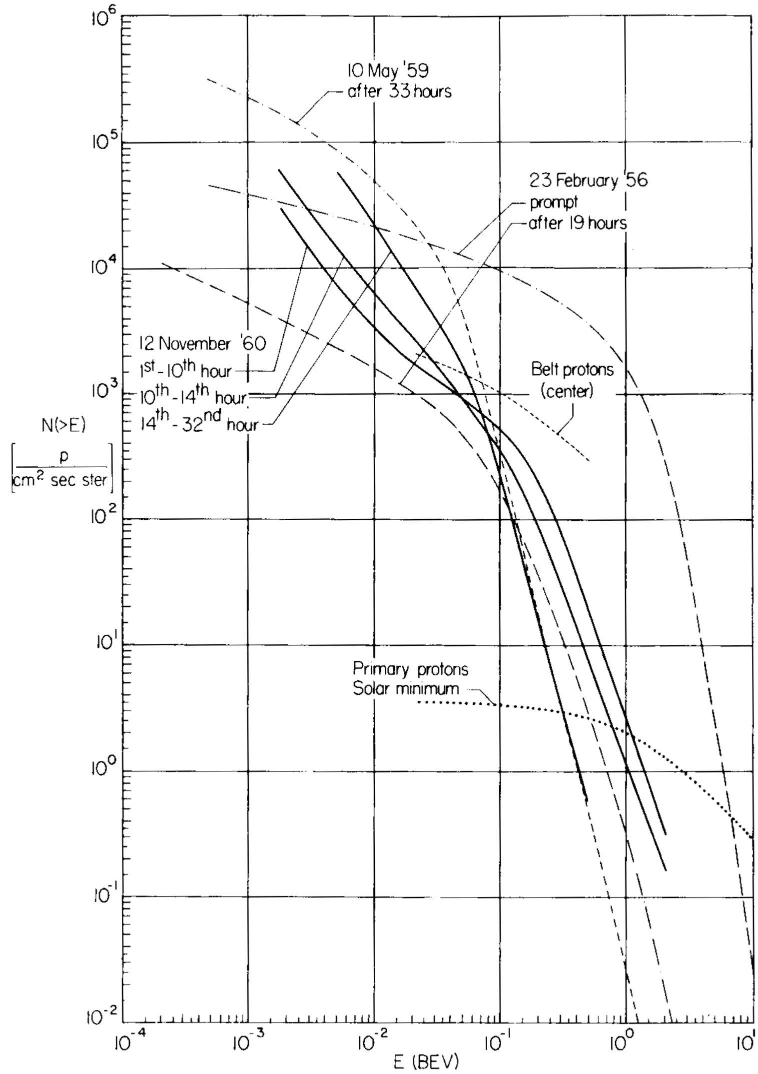

Figure 9.- Integral energy spectra of solar flare cosmic rays, inner belt protons and galactic primary protons. The spectra of February 1956, May 1959 and of galactic cosmic rays are plotted versus energy from the rigidity spectra given by Winckler (ref. 12) and Bailey (ref. 27). The spectra of 12 Nov. 1960 are extrapolated from spectra given by Fichtel Guss (Personal Communications) and measurements of Davis Olgivie (Personal Communications), van Allen (Explorer VII, Personal Communications), Winckler (ref. 25), and Ney (ref. 26). The inner belt proton spectrum (center) is obtained from Freeden and White's spectrum in 1200-kilometer altitude (ref. 5) by multiplication with 20.

During the high energy event on February 23, 1956, however, only a small - of course, not insignificant - part of the spectrum could have been cut off by the shielding amount of 30 g/cm^2. The step decrease of the spectrum begins not earlier than at approximately 1 Bev and we would have to use a water shield of 3m thickness to cut off all particles with lower energy, disregarding secondaries.

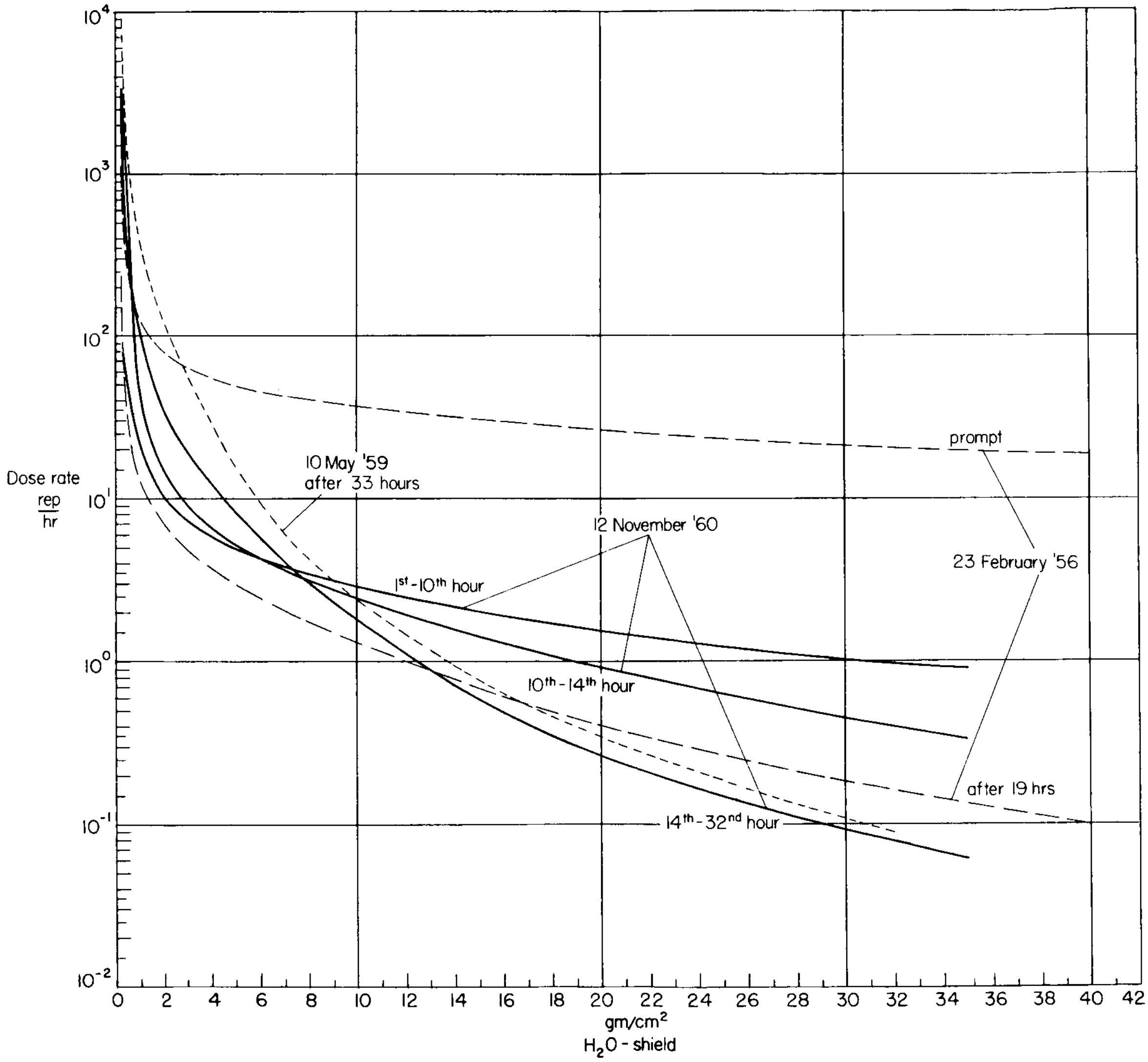

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Figure 10.- Proton dose rates in the center of spherical shields derived from the spectra in figure 9.

Dose Rate and Upper and Lower Limits of Doses

Quantitatively, the different penetration power of solar beams can be seen in figure 10, which shows the slower decrease of the dose rate with shielding thickness in high and medium energy events in comparison with the fast decrease in low energy events, respectively.

For estimating the radiation hazard of such proton events it is necessary not merely to consider the dose rate as a function of shielding thickness but the time integrated dose rate or the total dose accumulated during the entire event rather than the dose rate at particular instants. The biological effect is measured by the dose itself.

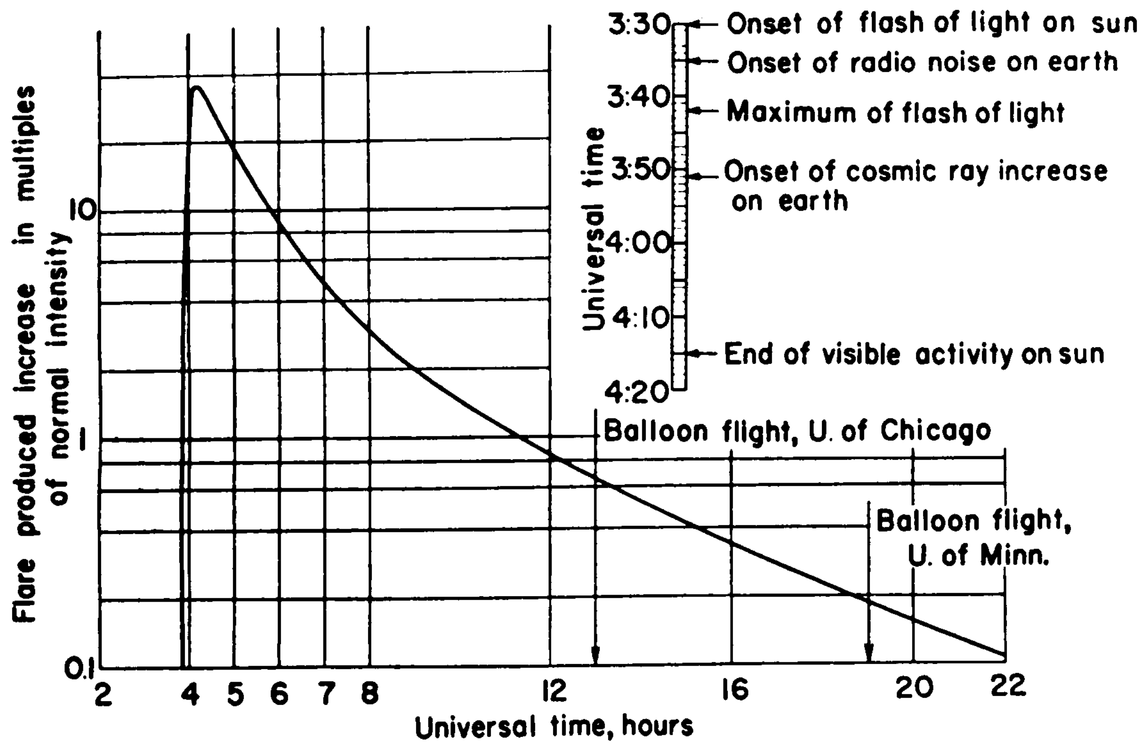

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Figure 11.- Cosmic ray neutron surge at sea level during large solar flare of February 23, 1956. Observed by Lockwood et al. at Durham, New Hampshire. (Reproduced from ref. 22.)

Each of these proton events has its own - often complicated - time history of intensities and spectra dependent on the source spectrum on the sun and magnetic fields between sun and earth. Frequently, rapid increase is followed first by a fast and later by a slow decrease of the intensity as shown in figure 11 (ref. 22). The surge of secondary neutrons at sea level in figure 11 reflects, of course, only the intensity of the high energy protons ($E > \mathrm{Bev}$) on top of the atmosphere.

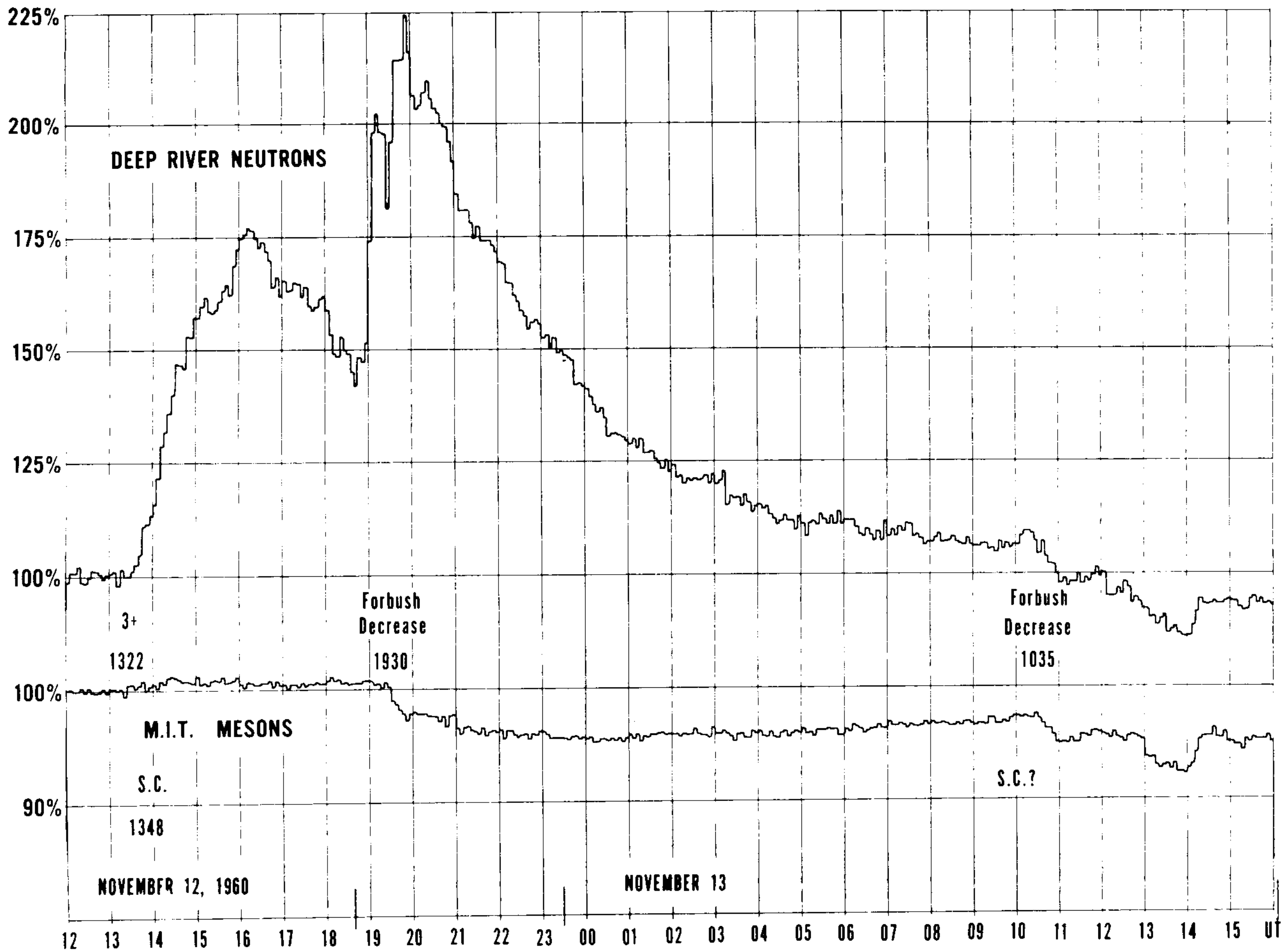

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Figure 12.- Neutron surge at sea level in Deep River, Canada from November 12 to November 15, 1960 and meson decrease measured at MIT. (J. F. Steljes, H. Carmichael, and K. G. McCracken, ref. 23.)

The increase and 50 percent decay period varies in duration from some 10 minutes (fast riser) to 24 hours (slow riser) in different events. Sometimes multiple peaks appear in the early phase. (See fig. 12, ref. 23.)

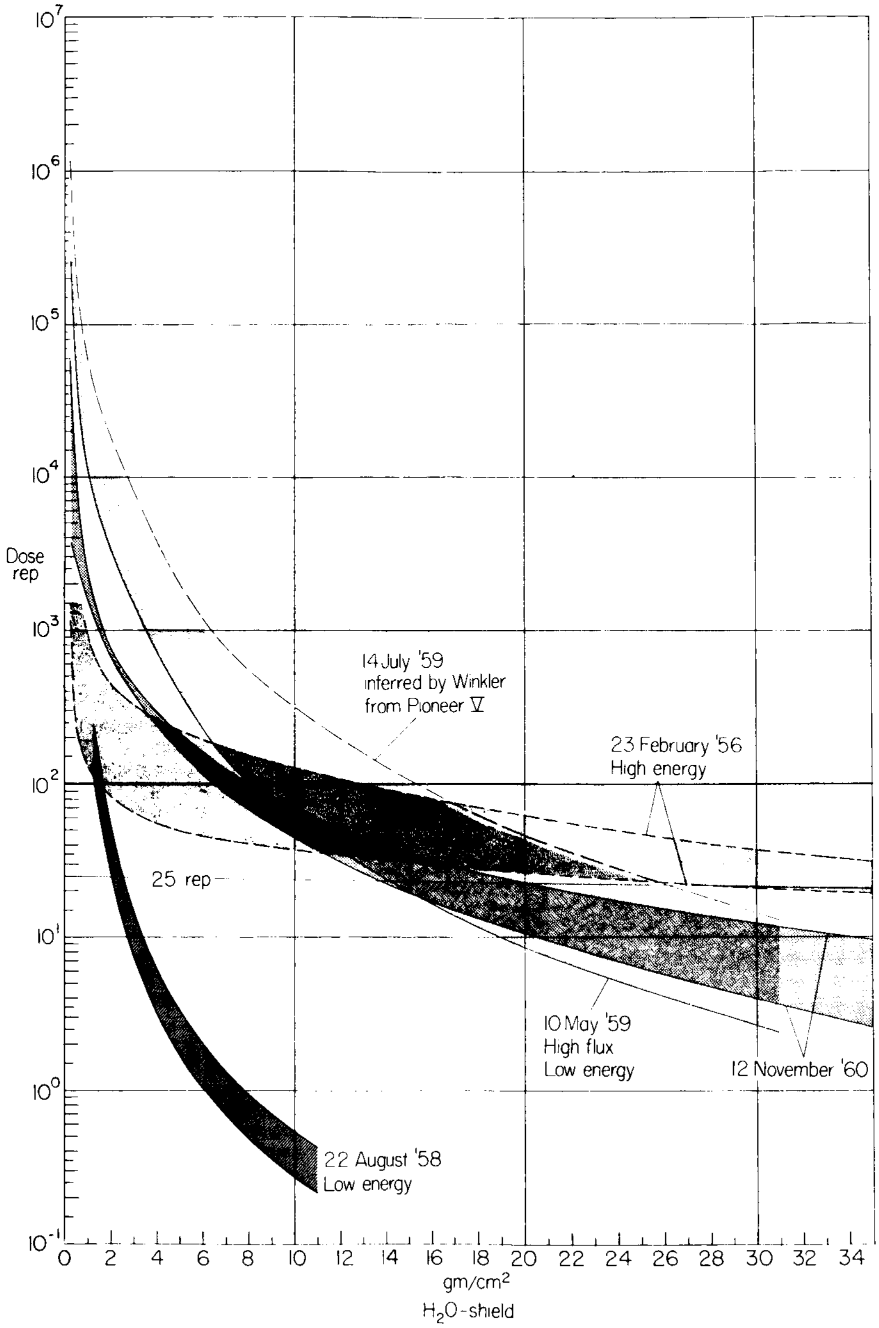

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Figure 13.- Estimates of upper and lower limits of doses in the center of spherical H_2O shields accumulated during extreme proton events.

Unfortunately, the intensities and the spectra during these early phases of maximum intensity that contribute most to the dose are not well known in many cases. For this reason, in figure 13 only rough estimates of upper and lower limits of doses in the various events can be given. These estimates are derived on the basis of the spectra, extrapolated in part, in figure 10 and time profiles of intensities extrapolated from neutron monitor, riometer (see ref. 28), balloon (refs. 25 and 26), rocket, satellite, and space probe measurements (ref. 24).

We note some dose values, as follows: Behind a shield of $2g/cm^2$ of H_2O a dose in the 1,000 rep range could possibly be received; behind a shield of $25g/cm^2$ of H_2O, the dose would be reduced to an upper limit of 50 rep in the high energy event of February 1956. In the low and medium energy events the upper limit would be below 25 rep behind a shield of $25g/cm^2$ of H_2O.

It should be mentioned that the upper limits of doses for the May and July 1959 events and for the February 1956 high energy event are probably assumed unnecessarily high (see refs. 25 and 28) and are more uncertain than the values given for November 12, 1960, where more spectra are available. It is, however, obvious that operating during such events in a lightly shielded space vehicle or staying on the moon surface protected only by a space suit would be dangerous, since radiation sickness can be expected at doses of 150 to 200 rem.

We may summarize these considerations with the statement that about $25 g/cm^2$ of H_2O equivalent shielding would be sufficient to reduce the exposure of the crew to 25 to 50 rep for every extreme event observed thus far. If two or three encounters are considered, total shield weights of 20 to $25 g/cm^2$ of H_2O would maintain the sum of the doses from the encounters at less than 100 rep. For a biological effectiveness of 1, a short time dose below about 100 rep produces only mild symptoms in 5 to 10 percent of those exposed or no effect other than minor blood changes followed by complete recovery. These estimates include in the author's opinion a substantial safety margin, since no selfshielding is taken into account and since, furthermore, the spectra for solar proton events and the time profiles of intensities used here are upper limits.

Of course the question of contribution of secondaries, especially neutrons, to the dose has to be investigated in more detail. A rough estimate (ref. 24), using the prompt spectrum of the February 23, 1956 high energy event, shows that the contribution of neutrons to the physical dose rate in rep/hr is about 15 percent behind a shield of $25 g/cm^2$ of H_2O. However, the contribution of secondary neutrons to the biological dose in rems should be higher and has to be taken into account for low energy events, too, which apparently can exhibit extreme proton fluxes in the low energy range with subsequent neutron fluxes that cannot be ignored. (See ref. 30.)

SUMMARY

In table I a summary of the radiation levels of galactic cosmic radiation, belt radiations, and solar cosmic radiation as obtained from the foregoing estimates are given.

Galactic cosmic radiation constitutes a comparatively minor hazard insofar as the over-all ionization dosage is concerned. At the low level of 0.5 rem/week or 1 rem/week during solar activity years, it has significance only on a trip of extended duration. In 1 to 2 years a dose of about 50 to 100 rem would be accumulated in a space ship during solar activity years. In adding up this amount of chronic low level irradiation to other more acute doses associated with belt and flare radiations, we have to apply a reduction factor to the galactic dose because of recovery of somatic damage, except for genetic effects, which are howeven considered as insignificant for doses in the order of 50 to 100 rem for one generation.

The effects of the heavy primary component of the cosmic ray beam are not known at present. The number of hits without any shielding in free space is low, on the order of 6 to 40 per cm^3 of tissue per day. It cannot be excluded that staying without substantial shielding for weeks or months in space would lead to injury. Fortunately shielding on the order of $20 g/cm^2$ of low Z-number material would reduce the number of heavy primary hits by a factor 1/15 or 1/3 during solar minimum or solar activity years, respectively. The number of hits decreases fast to zero with higher shield thicknesses, which latter should be available in form of propellent and supply in long-term excursions.

TABLE I.- ESTIMATED RADIATION EXPOSURE IN SPACE

I. Galactic cosmic radiation

	Gross ionization dosage	Heavy primary hits	
		Without shield	20 g/cm^2 of H_2O
During solar activity years	0.45 to 1.0 rem/week 25 to 50 rem/year	$6/cm^2$/day	$2/cm^3$/day

II. Belt radiation

Shield thickness	Inside spherical shields, neglecting selfshielding		
	2 g/cm^2 of H_2O	6 to 10 g/cm^2 of Al + steel	25 g/cm^2 of H_2O
Inner belt protons (center)	12 to 24 rep/hr	-----------	2.7 to 5.4 rep/hour
Outer belt electrons (center) X-radiation	---------------	<2 rem/hour	-------------------

III. Solar cosmic radiation

	Inside spherical shields, neglecting self-shielding	
	2 g/cm^2 of H_2O	25 g/cm^2 of H_2O
Low energy, extreme flux May, July 1959	2,500 to 15,000* rep	6 to 25 rep
Medium energy, extreme flux November 1960	600 to 800 rep	6 to 19 rep
High energy, high flux February 1956	80 to 400* rep	25 to 50* rep

*These values are extrapolated and highly uncertain.

The radiation of the earth radiation belts, although of 10^4 times higher proton intensity in the center of the inner belt, is nevertheless no major hazard, if the vehicle crosses the inner belt in 10 minutes, as was done by Pioneer III and IV. The proton dose is estimated to amount to only 3 to 6 rep for exit and return through the center in a lightly shielded vehicle. The secondary X-radiation from the belt electrons is probably held substantially below the level of 1 to 2 rem/hour by the normal content of low and high Z-number material of the walls of a typical vehicle, especially if these walls are covered by low Z-number material on the outside.

The most serious radiation problem for longer excursions into space during solar activity years is apparently posed by solar flare proton events. The potential radiation hazard depends on the date of the excursion. During solar minimum years no flares of importance are observed for more than a year. During solar activity years, even for excursion times of only 10 to 14 days, the probability of encountering an extreme event is not a negligible quantity. The absence of such events for such periods can also not be predicted from synoptical observations of solar phenomena with acceptable reliability at present. Adequate shielding for excursions of the order of weeks is recommended and becomes a necessity for trips of longer duration during solar activity years.

In table I upper and lower limits of doses as function of shielding thickness are given. Since more data become available especially about the intensities in the early phases of these events, it turns out that the upper limit of proton rep doses given in this table are assumed as unnecessarily high in some events. Without undue negligence we may consider in first approximation these upper limits as rem doses, including the contribution of secondaries, especially neutrons, to the biological dose, with the reservation that the shielding material has to be appropriately selected on the basis of detailed investigations. First estimates (ref. 30) show, that aluminum in thicknesses of $20 g/cm^2$ yields an appreciable contribution of evaporation neutrons to the rep dose (50-100 percent) in low energy events, H_2O however less than 20 percent.

Based on these upper limits the result is obtained that shielding equivalent to $25 g/cm^2$ of H_2O would have been sufficient for reducing the dose to 25 rem for every extreme low or medium energy event observed so far and for reducing the dose to 50 rem in passing through the event of February 23, 1956, the most intense high energy event of the last two solar cycles. With respect to the radiation hazard during excursions with a duration of weeks or more, it must be remembered that two or three solar proton events of comparable intensity frequently occur in short succession, so that the accummulated dose with shielding of $25 g/cm^2$ would increase to 75 to 100 rem. For longterm excursions due to the contribution of galactic cosmic rays, even heavier shielding may be necessary to reduce the contribution of flare events.

According to these preliminary estimates the radiation problem in space appears more serious than was suspected even 5 years ago, as Dr. Weinberg, Director of Oak Ridge national laboratory has stated (ref. 31). The feasibility of longer excursions also during solar activity years appears - of course - not questionable. If supplemental shielding is provided by appropriate positioning of equipment and supply the necessary additive weight for individual shielding should hardly surpass 25 percent of the space vehicle weight as it is envisioned even for smaller vehicles without regard to shielding.

APPENDIX

DEFINITION OF DOSE UNITS AND TERMS USED IN RADIOBIOLOGY (FOR SURVEY PURPOSES)

1 roentgen (r) is the amount of X-radiation which produces 2.08×10^9 ion pairs (one electrostatic unit of charge) per cm^3 of standard air (energy absorption 83.7 erg/g air).

1 rep (roentgen equivalent physical) = 93 erg/g, is the energy absorbed by 1 gm of soft tissue or water exposed to 1 roentgen of X-radiation ($\geqq$200 kev). This absorbed dose or simply fixed absorption per unit mass is a better measure for the physical and biological effect especially of soft X-radiation on nonaqueous tissue containing higher elements (e.g., bone) than the roentgen.

The rep or rad = 100 erg/g of physically absorbed energy is also the basis for estimating the biological effect of other kinds of radiation as of protons and heavier ions.

Low energy protons ($E < 10$ Mev), α and heavier ions, which ionize more densely along their paths have generally a higher biological effect than X-radiation at the same ionization or energy absorption per gram, i.e., at the same rep dose. Therefore the dose in rem (roentgen equivalent man, biological dose) is defined as the dose in rep increased by an appropriate multiplication factor, the relative biological effectiveness (RBE) of the specific radiation in question and for the specific organism or organ in question.

Dose in rem = dose in rep × RBE

The RBE factor can have values from 1 to 15 for relatively slow heavy particles.

The RBE of penetrating high energy proton beams in the 10th and 100th Mev ranges, which are mainly of concern in space vehicles, have in general only an RBE $\leqq$ 1.5, because of their low specific ionization. This refers to bone marrow, intestinal and general somatic damage if secondaries can be ignored. Special attention has to be given so that the eyes are not exposed without substantial prefiltration of low energy protons and fast neutrons.

LD50 (lethal dose for 50 percent) $\approx$ 450 rem

An acute total body dose of 450 rem is considered as lethal for 50 percent of men exposed.

150 to 200 rem: average acute total body dose for radiation sickness.

80 to 100 rem (acute, total body): "critical dose," produces light symptoms of the acute syndrome for 5 to 10 percent of those exposed to it during a period of about 1 day.

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